Simulation of Large Scenario and Recorded Moderate Earthquakes In The San Francisco Bay Area

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$M_w \sim 6.5-7.0$ October 21, 1868 Hayward Fault earthquake caused significant damage ... but only $\sim 3000$ people lived in the East Bay.
HPC ground motion simulations for large ($M_w$ 6.5-7.2) generic and Hayward Fault scenario earthquakes

- **SW4 FDTD simulations**
- **Fully 3D physics-based (wave equation) propagation:**
  - 3D Earth model & **topography**
  - Attenuation
  - Kinematic rupture models
  - **No stochastic time-series**
- This case ran on Cori at NERSC/LBNL
  - 25.6 billion grid points
  - Most of machine: 8192 nodes, 524,288 cores

- **This talk**
  - Motions agree well with GMM’s
  - Path and sit effects are significant
    - East-west differences across HF
  - Evaluate USGS 3D model with moderate earthquakes
SW4 enables accurate and efficient numerical simulation of earthquake ground motions

- Solves the elastodynamic equations of motion
  - Finite differences using summation-by-parts
  - Efficient for parallelization to run high-resolution

- SW4 includes:
  - Fully three-dimensional anelastic heterogeneity
    - \( V_p \) and \( V_S \), \( \rho \), \( Q_p \) and \( Q_S \)
  - Surface topography
  - Mesh refinement
  - Supergrid boundary conditions

- Recent improvements to parallel efficiency
  - Hybrid OpenMP/MPI
  - Great for many core nodes
  - Hybrid CPU/GPU version in progress...
Our goal is to compute broadband motions in 3D models with purely deterministic methods & HPC
Geology from Phelps et al. (2005) & Graymer et al. (2005)
Seismic properties from Brocher (2005)
Used in previous simulations studies
Shear wavespeed maps from the USGS 3D model: Vs at surface (with topography)

- min = 80 m/s, max = 3500 m/s; mean = 564 m/s, std = 287 m/s

Low wavespeeds amplify motions
Shear wavespeed maps from the USGS 3D model:
Depth to Vs = 1000 m/s

min = 0 m, max = 650 m; mean = 336 m, std = 236 m
Computational Domain

Domain size: 120 x 80 x 30 km

Grid spacing:
  15 m (fixed, no mesh refinement)
Number of grid points: 86.95 billion
Includes surface topography
  • Varies ~ 1250 m across domain
Minimum shear wavespeed: 500 m/s
Maximum frequency: 4.2 Hz (@ 8 ppw)
Seismogram time: 80-90 seconds
Time-histories computed on grid of stations
Computational domain, rupture model & USGS 3D Earth model

Domain:
120 x 80 x 30 km

Earth Model:
3D USGS model
Surface topography
Two Earth models considered: 1D FLAT & 3DTOPO
Peak Ground Velocity (PGV) maps

We considered two Earth models with the same rupture:
- **1DFLAT** – average 1D plane-layered model of KAG (BSSA, 2014)
- **3DTOPO** – USGS 3D model with surface topography

1DFLAT model has roughly symmetric pattern of PGV due to nearly vertical and strike-slip

3DTOPO model has more complex response
- Eastern side of HF has ~2x higher PGV
- Lower motions in CRO
- Basins amplify motions: SPB, SLB, SCV, LV, Delta
- Lower motions in high Vs area (mountains)
Resulting three-component ground motion (0-4 Hz): $R_{JB} = 4$ km from the Hayward Fault (Oakland)
Resulting RotD50 response spectrum: Comparison with PEER NGA-West2 GMM’s

Run: HF_M7.0_3DTOPO Station: S_30_22

- $*\sigma$
- $1/\sigma$

Pseudospectral Acceleration, g (5% damping)

Un-/poorly resolved

Well resolved

$RJ_B = 4.0 \text{ km}$

$vs30 = 500.0 \text{ m/s}$

$z_{1.0} = 0.05 \text{ km}$

$z_{2.5} = 0.85 \text{ km}$

$f_{max} = 4.2 \text{ Hz}$
PGA & PGV versus distance with ASK14 GMPE

* PGA biased low for 1DFLAT, user error problem with Q

1DFLAT

3DTOPO

bias_pga

bias_pgw

bias_pga

bias_pgw
Bias relative to ASK14 GMPE

For each GMIM (e.g. PGA, PGV, Sa_{(period)}) form ratio: simulation/GMPE prediction

Box-and-whisker plots show: median (thick black), 25% and 75% quartiles (box), 1.5 times inter-quartile range (1.5IQR, whiskers) and outliers (circles)

— — — typical GMM 1σ uncertainty (0.7, or factor 2)

All median values are within GMPE 1σ uncertainties

3DTOPO shows more variation than 1DFLAT, especially short-periods
3DTOPO Peak Ground Velocity (PGV)
Effect of 3D structure (3DTOPO/1DFLAT)

Amplification over low wavespeeds
Deamplification over high wavespeeds
Shear wavespeeds across the northern Hayward Fault

View looking South

Orinda  Oakland

Differences of Vs on either side of the Hayward Fault persists to ~10 km
Recent consideration of 5 five events near Berkeley-Oakland-Orinda-Lafayette

Events
- $M_w \geq 4.0$
- BSL moment tensor
- NCSS double-difference origin

Waveforms
- Berkeley Digital Seismic Network (broadband)
- Northern Hayward Fault Network (borehole)
Evaluate goodness-of-fit by cross-correlation on rotated, filtered waveforms

**Plot shows 3-component wf’s:**
- Observed waveform
- Synthetic waveform
  - "shifted with optimal delay

Compute from peak of cross-correlation:
- delay time
- correlation coefficient

Delay time indicates bias in Earth model

CC indicates accuracy of the source & Earth models
Lincoln Heights to BKS – East of HF

Velocity response
Absolute amplitudes
Filter 0.1-1 Hz
Each data-syn pair x-correlated
Shift by delay time, dt
Compute cc

1D (KAG14)

3D (USGS)

USGS 3D model east of the HF appears to be too slow?

dt = -0.35  
cc = 0.58

dt = -1.25  
cc = 0.68

3D model gives visually better fit
Lincoln Heights to BRK – West of HF

USGS 3D model west of the HF appears to be less biased than the east side

- $dt = -0.65$
- $dt = -0.40$
- $cc = 0.83$
- $cc = 0.7$
Lake Temescal event to BRK (west) & BKS (east)

USGS 3D model west of the HF appears to work reasonably well

USGS 3D model east of the HF appears to be too slow?
Conclusions

- **Our M\textsubscript{W} 7.0 HF earthquake simulations are the highest resolution to date for SFBA**
  - Broadband, fully 3D Earth structure, topography & attenuation
    - SW4’s mesh refinement is key to increasing resolved frequencies
  - Provides new data for engineering applications, particularly near-fault strong motions

- **Median GMIM’s are consistent with GMM’s**

- **3D wave propagation leads to more ground motion intensity variability than 1D**
  - We must advance fully 3D deterministic HPC modeling

- **SW4 improvements are making earthquake ground motion simulations easier and faster**
  - Need to run suites of ruptures for a given scenario

- **Current USGS 3D model needs improvement**
  - Some encouraging fits to waveforms, but possible systematic bias
  - Importantly, shear wavespeeds in East Bay Hills may be too low
Next steps

- Run more Hayward Fault scenarios using the current USGS 3D model
  - Target higher frequency, 8-10 Hz, demonstration calculation
  - Lower frequency (say 3-4 Hz) suite of ruptures
    - How do slip distribution, directivity, rise time, rupture speed impact motions?
    - More systematic analysis of path effects

- Evaluate the USGS 3D model with moderate earthquakes
  - What frequencies, paths, distances can be consistently modeled?
  - Is there systematic bias, e.g. low wavespeeds in East Bay Hills?

- 3D Earth model in SFBA needs to be improved
  - Ideally, by full waveform inversion
  - Use moderate earthquake data to improve waveform fits
BACKUP SLIDES
Rupture model from Graves & Pitarka (2016)

Asperity near locked segment, Oakland

Slip (cm)

Duration (s)

Rake Angles

Along strike, km

Down dip, km

SRF: m7.0-50.0x20.0.s600.0_v5.1.srf
Total seismic moment: 3.55E+19 N-m
Moment magnitude, Mw: 7.00
Peak & mean slip: 383 102 cm
Rake range: -18 - 85 degrees
Latest slip start: 21.8 s
Earthquake starts at the hypocenter (green star)
Magnitude of velocity ($|\vec{v}|$) animation for Hayward Fault $M_W$ 7.0 scenario (0-4 Hz) with 3D Earth model and surface topography

Waveforms output for 2 km grid
Data available upon request
Fault-normal velocity waveforms show stronger motions on eastern side of Hayward Fault.

Waveforms output for 2 km grid. Data available upon request.
1D models and shear wavespeed profiles across the Hayward Fault

Near-Surface Geotechnical

We are missing low $v_s$ geotechnical when $v_s$ limited to $\geq 500$ m/s

Upper Crust

Significant $v_s$ contrast across HF
Franciscan $v_s >$ Great Valley $v_s$

Of course, low $v_s$ materials respond non-linearly at high strains
Effect of topography (3DTOPO/3DFLAT)

Amplification on hill tops
Deamplification in valleys